

Effective Radiation Dose, Time, and Contrast Medium to Measure Fractional Flow Reserve

Argyrios Ntalianis, MD, PhD, Catalina Trana, MD, Olivier Muller, MD, PhD, Fabio Mangiacapra, MD, Aaron Peace, MD, PhD, Carina De Backer, RN, Liesbeth De Block, RN, Eric Wyffels, MD, Jozef Bartunek, MD, PhD, Marc Vanderheyden, MD, Alex Heyse, MD, Frederic Van Durme, MD, Luc Van Driessche, MD, Jo De Jans, RN, Guy R. Heyndrickx, MD, PhD, William Wijns, MD, PhD, Emanuele Barbato, MD, PhD, Bernard De Bruyne, MD, PhD

Aalst, Belgium

Objectives This study sought to define the additional effective radiation dose, procedural time, and contrast medium needed to obtain fractional flow reserve (FFR) measurements after a diagnostic coronary angiogram.

Background The FFR measurements performed at the end of a diagnostic angiogram allow the obtaining of functional information that complements the anatomic findings.

Methods In 200 patients (mean age 66 ± 10 years) undergoing diagnostic coronary angiography, FFR was measured in at least 1 intermediate coronary artery stenosis. Hyperemia was achieved by intracoronary ($n = 180$) or intravenous ($n = 20$) adenosine. The radiation dose (mSv), procedural time (min), and contrast medium (ml) needed for diagnostic angiography and FFR were recorded.

Results A total of 296 stenoses (1.5 ± 0.7 stenoses per patient) were assessed. The additional mean radiation dose, procedural time, and contrast medium needed to obtain FFR expressed as a percentage of the entire procedure were $30 \pm 16\%$ (median 4 mSv, range 2.4 to 6.7 mSv), $26 \pm 13\%$ (median 9 min, range 7 to 13 min), and $31 \pm 16\%$ (median 50 ml, range 30 to 90 ml), respectively. The radiation dose and contrast medium during FFR were similar after intravenous and intracoronary adenosine, though the procedural time was slightly longer with intravenous adenosine (median 11 min, range 10 to 17 min, $p = 0.04$) than with intracoronary adenosine (median 9 min, range 7 to 13 min). When FFR was measured in 3 or more lesions, radiation dose, procedural time, and contrast medium increased.

Conclusions The additional radiation dose, procedural time, and contrast medium to obtain FFR measurement are low as compared to other cardiovascular imaging modalities. Therefore, the combination of diagnostic angiography and FFR measurements is warranted to provide simultaneously anatomic and functional information in patients with coronary artery disease. (J Am Coll Cardiol Intv 2010;3:821–7) © 2010 by the American College of Cardiology Foundation

Revascularization of hemodynamically nonsignificant stenoses does not improve clinical outcome (1). Outcome benefit is the greatest when demonstrable ischemia is present prior to revascularization and relieved by the intervention (2).

Nevertheless, a minority of patients undergoing percutaneous coronary intervention (PCI) have not had a noninvasive stress test prior to catheterization (3), even in the case of stable coronary artery disease and elective PCI (4). When revascularization is based mainly on angiographic guidance, it is unavoidable that a number of hemodynamically nonsignificant stenoses will be revascularized, and that a number of stenoses deemed hemodynamically nonsignificant will be deferred inappropriately (5).

Because the combination of an anatomic and functional standard appears to be an appropriate decision-maker for revascularization (6), but the necessary functional information is often lacking or inconclusive, fractional flow reserve (FFR) measurements are often performed to complement a diagnostic coronary angiography. Concern has been raised about the radiation dose and amount of contrast medium associated with cardiac imaging. There is also a perception that FFR might add an unreasonable amount of time, contrast, and radiation exposure to a diagnostic study.

Abbreviations and Acronyms

FFR = fractional flow reserve

PCI = percutaneous coronary intervention

The purpose of this study was to investigate the additional effective radiation dose, amount of contrast medium, and time needed for FFR measurements in patients undergoing diagnostic coronary angiography.

Methods

Study population. Between January 2009 and September 2009, 803 patients underwent FFR measurements in Cardiovascular Center Aalst. In 438 patients, FFR was performed during PCI, and in 47 patients, pressure measurements were obtained in renal artery stenoses and were excluded. In 316 patients, FFR was obtained at the end of a diagnostic procedure. Of those, 116 were excluded because radiation dose was not recorded properly. Finally, 200 patients were prospectively included in the present registry. In all of them, FFR measurements were performed at the end of a diagnostic angiogram to determine the appropriate treatment strategy. The exact dose of radiation, the time, and the amount of contrast medium were carefully recorded. No patients were excluded because of an unfavorable anatomy.

Study protocol. Biplane left ventricular and coronary angiography were obtained in all patients. The number and type of projections was left to the operator's discretion. For all the coronary artery stenoses assessed by FFR, quantitative coronary angiography analysis was performed offline in 2 orthogonal projections using an automated contour de-

tection algorithm (ACOM, PC version 5.01, Siemens Medical Systems, Inc., Cary, North Carolina).

FFR assessment. Fractional flow reserve was measured as previously described (7). Briefly, after intravenous administration of heparin (100 U/kg of body weight), and intracoronary administration of isosorbide dinitrate (200 μ g), a pressure monitoring guidewire (Certus PressureWire, Radi Medical Systems, Uppsala, Sweden) was calibrated and introduced in the guiding catheter. Before advancing the pressure sensor distal to the stenosis, the pressures recorded by the sensor and by the guiding catheter were equalized. For ostial lesions, equalization of the pressures was obtained in the aortic root, outside the diseased ostium of the vessel. Then, the pressure wire was advanced distal to the coronary artery stenosis. In every case, the position of the wire was filmed with the administration of contrast medium to ensure the correct placement of the wire.

Hyperemia was obtained after administration of intravenous (140 μ g/kg/min, $n = 20$) or intracoronary adenosine (bolus injection of 50 μ g for both left and right coronary artery, $n = 180$). Fractional flow reserve was defined as the ratio of the mean arterial pressure distal to the stenosis measured by the pressure wire sensor to the mean aortic pressure at the tip of the guiding catheter during hyperemia. When intracoronary adenosine was used to induce hyperemia, FFR was measured twice and the average FFR value of both measurements was taken. After FFR assessment, the pressure sensor was pulled back at the tip of the guiding catheter and both pressures (guiding and wire) were carefully checked. In case of uneven pressures, equalization of the pressures and FFR were repeated. If the pressure ratio was equal to 1, the pressure wire was removed out of the guiding catheter and a final control coronary angiogram of the studied vessel was performed.

Effective radiation dose, procedure time, and contrast medium. The effective radiation dose (mSv), the procedure time (min), and contrast medium (ml) were recorded separately for the diagnostic angiography and for the manipulations related to the FFR measurements. For the diagnostic coronary angiogram, all parameters were recorded between the anesthesia of the skin and the moment the operator decided to obtain FFR measurements. For the FFR measurements, all parameters were recorded from the moment the operator decided to obtain FFR measurements until the end of the final control coronary angiogram just after having obtained the FFR values and removing the pressure monitoring guidewire. This includes the exchange of a diagnostic catheter for a 6-F guide catheter and the placement of a Y-connector between the manifold and the guide catheter. The operators were blinded to the radiation, time, and contrast values measured before and during FFR assessment. For most patients, the operator was even blinded to the fact that these measurements were recorded.

The “absorbed radiation dose” in both biplane X-ray systems used (Siemens AXIOM Artis 2004 and Bior) was automatically calculated in mGy/cm². The absorbed dose corresponds to the energy absorbed per unit of body mass as a result of exposure to ionizing radiation (8). However, to estimate the probability of adverse biological effects induced by the radiation, the “effective dose” was also calculated (mSv). For the calculation of the effective dose, either the Monte Carlo-based computer simulation as described by Servomaa et al. (9) or the tables of conversion factors as defined by the National Radiological Protection Board (10) can be used. They both implement a special conversion factor as defined by the field size, filtration, tube potential, geometry, and type of filming (fluoroscopy or cineradiography) to convert absorbed into effective dose (11,12). In our catheterization laboratory, additional copper filtration is present in both X-ray equipments and the specific conversion factor was previously calculated as of 0.203 (12). In our registry, to convert the absorbed dose into the effective dose of radiation, the conversion factor was multiplied with the absorbed dose as previously described (12).

Statistical analysis. SPSS version 16.0 (SPSS, Inc., Chicago, Illinois) was used for the statistical analysis of the data. Continuous variables are expressed as mean \pm SD. Paired and unpaired Student *t* tests were used to compare normally distributed variables. Wilcoxon and Mann-Whitney non-parametric tests were used for the comparison of the non-Gaussian distributed variables. One-way analysis of variance and the parametric Bonferroni post hoc test or Kruskal-Wallis and the nonparametric Dunn post hoc test were used for the comparison of radiation, time, and contrast during 1-, 2-, and 3-vessel (or more) FFR measurements. Categorical variables are expressed as frequencies and percentages. Radiation, time, and contrast during FFR obtained after intracoronary adenosine administration were compared with radiation, time, and contrast during diagnostic coronary angiography. The same parameters during

multilesion FFR measurements were compared with 1-lesion FFR measurements. Radiation, time, and contrast values after intracoronary adenosine administration were also compared with radiation, time, and contrast after intravenous adenosine infusion. The *p* values <0.05 were considered statistically significant.

Results

Baseline characteristics. The data of 296 stenoses assessed by FFR after a diagnostic coronary angiography in 200 consecutive patients (1.5 ± 0.7 per patient) were included in the final analysis. Demographic and clinical data of the patients are shown in Table 1. The majority of the study population were men presenting with stable angina. Almost one-half of the patients had a PCI in the past and one-fourth had a previous history of myocardial infarction. Mean left ventricular end-diastolic pressure and ejection fraction were 15 ± 6 mm Hg and $68 \pm 17\%$, respectively (Table 2). The mean percentage diameter stenosis by quantitative coronary angiography and mean FFR values were $42 \pm 14\%$ and 0.84 ± 0.09 , respectively (Table 2). No complication was observed in relation to the FFR measurements.

Total values of radiation, time, and contrast. The median values of radiation, time, and contrast needed to measure FFR were lower than the corresponding values needed for diagnostic left heart catheterization and coronary angiogram (Fig. 1). On average, an additional median radiation of 4 (range 2.4 to 6.7) mSv ($30 \pm 16\%$ of the total radiation needed for diagnostic catheterization), an additional median time of 9 (range 7 to 13) min ($26 \pm 13\%$ of the total time needed for diagnostic catheterization), and an additional median contrast of 50 (range 30 to 90) ml ($31 \pm 16\%$ of the total contrast needed for diagnostic catheterization) were required to obtain FFR measurements. Expressed per lesion measured, the corresponding median values of additional

Table 1. Clinical Characteristics, Treatment, and Laboratory Data of the Study Population

Characteristics	All-Study Population (n = 200)	Intracoronary Adenosine (n = 180)	Intravenous Adenosine (n = 20)	p Value
Age, yrs	66 \pm 10	66 \pm 10	68 \pm 12	0.56
Men/women, %	76/24	76/24	70/30	0.58
BMI, kg/m ²	27 \pm 4	27 \pm 4	26 \pm 4	0.48
LAD/LCx/RCA/Other*	51/22/20/7	50/23/20/7	64/12/12/12	0.43
SA/UA/SI/Other†	40/6/7/47	40/5/7/48	33/7/0/60	0.60
Previous MI, %	23	23	13	0.52
Previous PCI, %	48	49	33	0.29
Previous CABG, %	6	6	13	0.24

The *p* values indicate the statistical difference between the intracoronary and intravenous adenosine groups. *Vessel assessed by fractional flow reserve. †Clinical indication for catheterization.
BMI = body mass index; CABG = coronary artery bypass grafting; LAD = left anterior descending artery; LCx = left circumflex artery; MI = myocardial infarction; PCI = percutaneous coronary intervention; RCA = right coronary artery; SA = stable angina; SI = silent ischemia; UA = unstable angina.

Table 2. Hemodynamic, Angiographic, and Functional Measurements

	All-Study Population (n = 200)	Intracoronary Adenosine (n = 180)	Intravenous Adenosine (n = 20)	p Value
LVEF, %	68 ± 17	68 ± 17	71 ± 13	0.49
LVEDP, mm Hg	15 ± 6	15 ± 7	17 ± 5	0.39
HR, beats/min	70 ± 12	70 ± 12	69 ± 11	0.93
DS, %	42 ± 14	42 ± 13	40 ± 16	0.39
MLD, mm	1.7 ± 0.5	1.7 ± 0.5	1.6 ± 0.5	0.71
RD, mm	2.9 ± 0.7	2.9 ± 0.7	2.7 ± 0.6	0.95
FFR	0.84 ± 0.09	0.84 ± 0.09	0.84 ± 0.07	0.98

The p values indicate the statistical difference between the intracoronary and intravenous adenosine groups.

DS = diameter of stenosis; FFR = fractional flow reserve; HR = heart rate; LVEDP = left ventricular end-diastolic pressure; LVEF = left ventricular ejection fraction; MLD = minimum lumen diameter; RD = reference diameter.

radiation, time, and contrast are 2.8 (range 1.7 to 4.5) mSv, 7 (range 5 to 9) min, and 35 (range 25 to 50) ml (Fig. 2). The additional radiation, time, and contrast needed for FFR, as expressed per lesion measured, correspond to 22%, 20%, and 23% radiation, time, and contrast on top of the diagnostic left heart catheterization (Fig. 2).

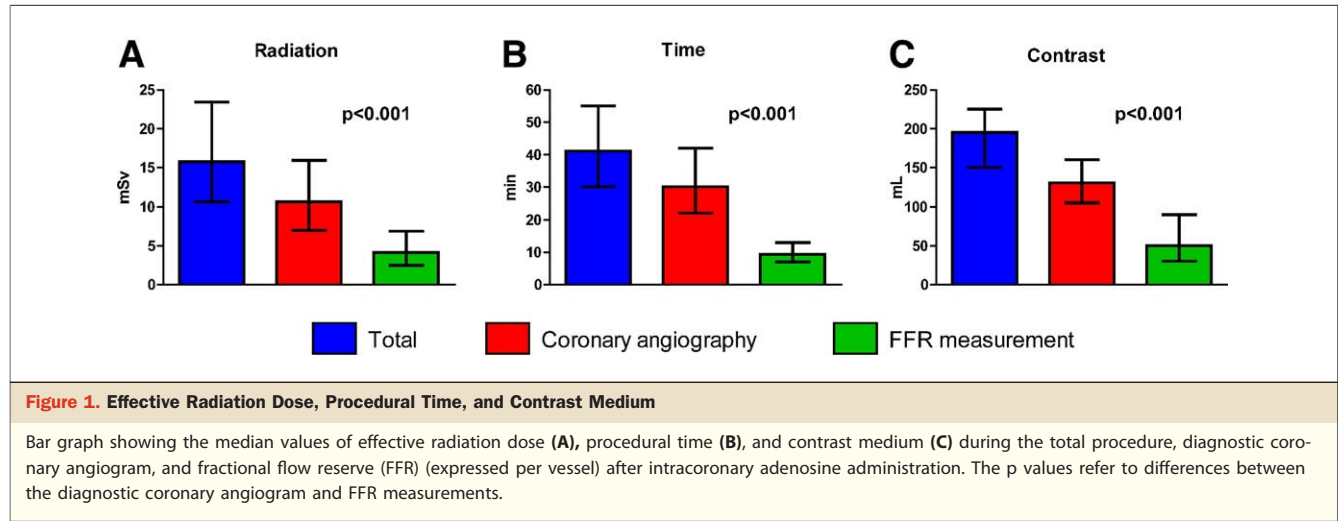
Effect of number of vessels measured. The FFR measurements were performed in 1 lesion in 126 patients (63%), in 2 lesions in 53 patients (26%), and in 3 or more lesions in 21 patients (11%). Total radiation, time, and contrast were similar when FFR was measured in 1 or 2 lesions. In contrast, total radiation, time, and contrast increased slightly when 3 or more lesions were measured by FFR (median 14 [range 9 to 21] mSv vs. 17 [range 15 to 27] mSv, median 40 [range 30 to 52] min vs. 49 [range 40 to 61.5] min, and median 175 [range 145 to 219] ml vs. 225 [range 195 to 254] ml for 1 and 3 vessels, respectively; $p < 0.05$) (Fig. 3). The radiation, time, and contrast remained unchanged during coronary angiogram, and thus the increase of total radiation, time, and contrast when 3 or more lesions were measured by FFR is attributed to a slight increase of radiation, time, and contrast during FFR measurements

(median 2.8 [range 1.7 to 4.5] mSv vs. 6.6 [range 4.3 to 8.4] mSv, median 7 [range 5 to 9] min vs. 15 [range 12 to 17] min, and median 35 [range 25 to 50] ml vs. 90 [range 52.5 to 108] ml for 1 and 3 vessels, respectively; $p < 0.05$).

Intracoronary versus intravenous adenosine. Total radiation and contrast did not vary according to the route of administration of adenosine. Yet, in patients in whom hyperemia was induced by intravenous adenosine, the time needed to obtain FFR measurements was slightly longer (Table 3, Fig. 4).

Discussion

The main finding of the present study is that the additional radiation, time, and contrast required to define the hemodynamic significance of coronary artery stenoses using FFR is limited as compared to other cardiac imaging modalities. The additional functional information provided by FFR on top of the angiographic anatomic information for a single coronary artery stenosis can be reliably obtained at the cost of an extra 2.8 mSv of effective radiation dose, 7 min of procedural time, and 35 ml of contrast medium.



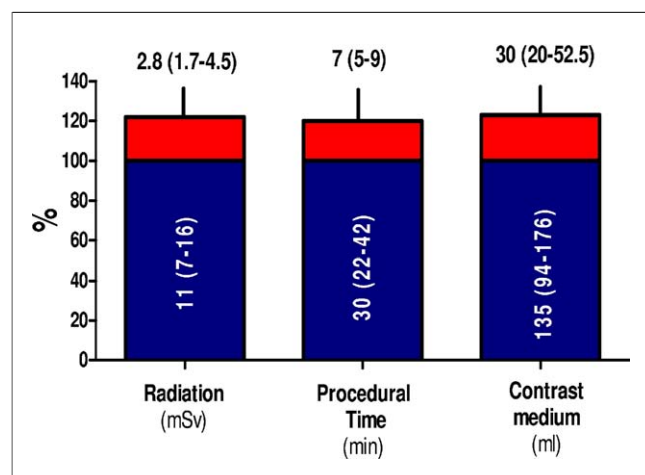


Figure 2. Per-Lesion Effective Radiation, Procedural Time, and Contrast Medium

Bar graph showing the median values of the additional radiation, procedural time, and contrast medium needed for fractional flow reserve measurements (as expressed per lesion) after intracoronary adenosine. Abbreviation as in Figure 1.

FFR as a surrogate for noninvasive testing. The majority of patients undergoing PCI never underwent any kind of noninvasive stress testing (3,4). Although the limitation of angiography in assessing lesion severity is widely acknowledged, most decisions about revascularization are taken merely on the basis of the angiogram. Pressure-derived FFR provides the same information as myocardial perfusion imaging except that: 1) FFR is more accurate to defining the severity of angiographic intermediate stenoses that induce ischemia; 2) FFR has a better spatial resolution; and 3) most importantly, it is available in the catheterization laboratory, the very place where the treatment can be applied (7). Therefore, the combination of diagnostic angiography and FFR measurements provides

Table 3. Median Values With Their IQR of Radiation, Time, and Contrast After Administration of Intracoronary and Intravenous Adenosine

	Intracoronary Adenosine (n = 180)	Intravenous Adenosine (n = 20)	p Value
Radiation, mSv			
CA	11 (7–16)	9 (4.5–13)	0.18
FFR	4 (2.4–6.7)	3.9 (1.6–6.7)	0.36
Time, min			
CA	30 (22–42)	28 (20–39)	0.19
FFR	9 (7–13)	11 (10–17)	0.04
Contrast medium, ml			
CA	130 (105–160)	135 (94–176)	0.78
FFR	50 (30–90)	38 (24–60)	0.08

CA = coronary angiography; IQR = interquartile range; other abbreviation as in Table 2.

the unique opportunity to obtain anatomic and functional information at the same place and at the same time.

Effective dose of radiation and cardiac imaging. Concerns have been raised about the dose of ionizing radiation related to imaging modalities (8,13,14). Deterministic effects such as skin erythema, epilation, and cataract formation are dependent on the radiation dose. Also, exposure to low-dose ionizing radiation confers a definite, albeit low, long-term risk of cancer and leukemia (15–19). In a recent cross-sectional international multicenter study of estimated radiation dose in 1,965 patients undergoing coronary computed tomography angiography (18), the typical effective radiation doses ranged from 4.5 to 29 mSv (average 12 mSv). Similarly, myocardial perfusion imaging is typically associated with an average effective radiation dose of 15.6 mSv (13). Thus, as shown in the present study, the total effective radiation dose generated by the combination of left ventricular and coronary angiography and FFR (approximately 16 mSv) is similar to *either* myocardial perfusion imaging *or* computed tomography coronary angiography.

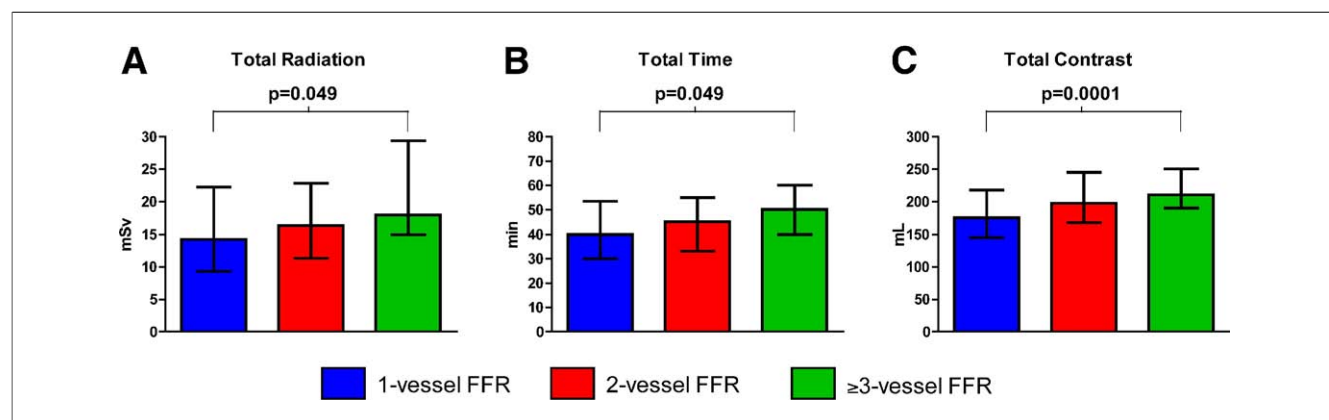
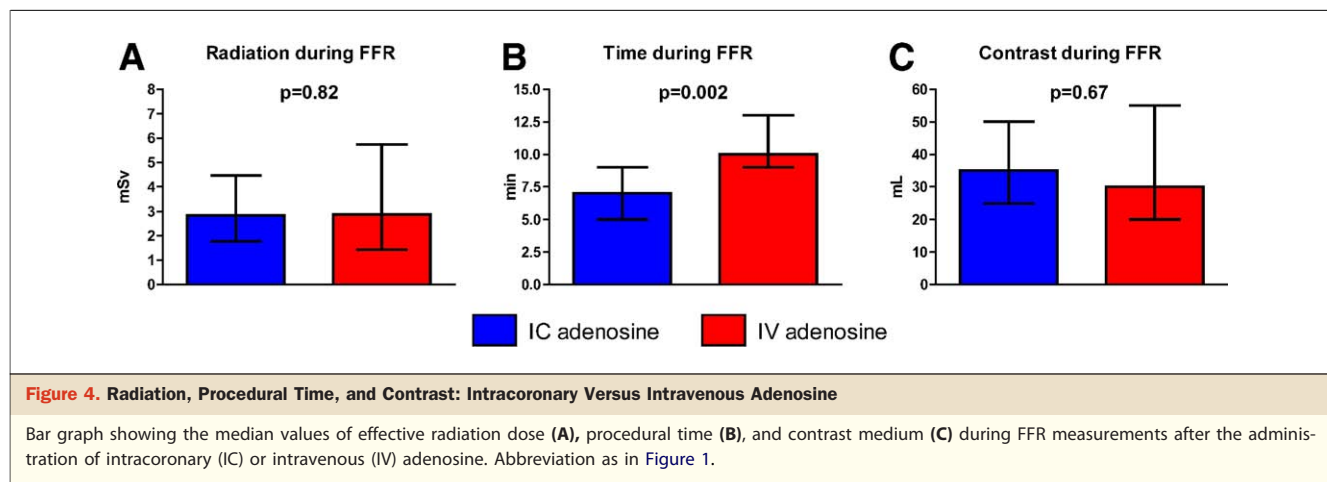


Figure 3. Effective Radiation Dose, Procedural Time, and Contrast Medium in Multivessel Disease

Bar graph showing the median values the additional total effective radiation (A), procedural time (B), and contrast medium plots (C) needed to measure FFR in 1, 2, or 3 stenoses using intracoronary adenosine. Abbreviation as in Figure 1.



The diagnostic workup of patients with known or suspected coronary artery disease often comprises several imaging procedures exposing them to substantial doses of ionizing radiations (17).

Duration of FFR measurements. The additional time needed to obtain FFR measurements is a reason of concern in many busy catheterization laboratories. This time is critically dependent on logistic factors. If the interface has to be switched on, connected, and configured each time an FFR measurement is contemplated, this additional time burden will be taken as a reason not to perform the measurement. The same holds for the preparation of the hyperemic agent. In the present study, the decision to measure FFR was taken after the diagnostic angiogram and was therefore always “unplanned.” The stopwatch was set on the request of the guiding catheter and was stopped after the control coronary angiogram just after the removal of the pressure wire from the coronary tree. On average, the time needed to obtain FFR measurements at the end of a diagnostic angiogram was 7 min in 1 coronary artery and 15 min in 3 or more coronary arteries. This time is obviously much shorter than that needed to obtain a myocardial perfusion imaging, a stress echocardiogram, or any other form of functional imaging. This prolongation in 3-vessel disease patients was mainly related to the fact that the guide catheter had to be exchanged. It is technically possible to measure FFR with a diagnostic catheter (20). In our experience, however, wire manipulations are more difficult than through a guide catheter. In addition, when PCI is needed, an additional catheter exchange is necessary. In the present study, a modest but significant prolongation (by 2 min) of the time needed to obtain the FFR measurement was observed when adenosine was given intravenously. This is essentially related to logistic factors. In this respect, it is important to emphasize that in all cases, intravenous adenosine was given via a transfemoral line that was installed while the nurse was preparing the intravenous infusion.

Contrast medium and FFR. The risk of acute renal failure after administration of contrast medium is proportional to the amount of contrast medium and to the pre-existing glomerular filtration rate (21). Typically, the amount of contrast medium given for coronary computed tomography angiography is approximately 100 ml. The present study indicates that even when multiple lesions are assessed by FFR (≥ 3), the extra amount of contrast medium required is relatively limited (≈ 50 ml). Implementing FFR for all dubious stenoses, the actual risk of acute kidney injury should diminish rather than expand, because almost one-third of angiographically “significant” stenoses appear to be hemodynamically nonsignificant (22). Future prospective trials should definitely answer this question, although, in multivessel PCI, the amount of contrast medium was smaller when the need for revascularization was guided by FFR than when it was guided solely on the basis of the angiogram (23).

Study limitations. The present data were obtained in a center performing more than 1,000 FFR per year. More than one-third of these measurements are obtained in the setting of diagnostic angiography when a doubt about the optimal treatment persists at the end of the angiogram. These results may not necessarily be generalized to laboratories or operators that only infrequently perform FFR.

Clinical implications. To avoid unnecessary catheterization and to guide the treatment, functional testing should be obtained in patients with suspected or known coronary artery disease before considering catheterization. Yet, real-world data (3,4) indicate that only a minority of patients undergo noninvasive imaging prior to angiography. Measuring FFR at the end of a diagnostic angiogram is an alternative way to obtain the same information (6). The low additional effective radiation dose, procedural time, and volume of contrast medium required for FFR underscore its applicability and safety. These findings further support an all-in-one approach in patients with coronary artery disease

and equivocal coronary artery stenoses, that is, obtaining a complete diagnostic anatomic and functional workup and deciding the appropriateness of revascularization or not at the same place and at the same time.

Reprint requests and correspondence: Dr. Bernard De Bruyne, Cardiovascular Center Aalst, Onze-Lieve-Vrouw Clinic, Moorselbaan, 164, Aalst B-9300, Belgium. E-mail: bernard.de.bruyne@olvz-aalst.be.

REFERENCES

1. Pijls NH, van Schaardenburgh P, Manoharan G, et al. Percutaneous coronary intervention of functionally nonsignificant stenosis: 5-year follow-up of the DEFER study. *J Am Coll Cardiol* 2007;49:2105-11.
2. Shaw LJ, Berman DS, Maron DJ, et al., on behalf of COURAGE Trial Investigators. Optimal medical therapy with or without percutaneous coronary intervention to reduce ischemic burden: results from the Clinical Outcomes Utilizing Revascularization and Aggressive Drug Evaluation (COURAGE) trial nuclear substudy. *Circulation* 2008;117:1283-91.
3. Topol EJ, Ellis SG, Cosgrove DM, et al. Analysis of coronary angioplasty practice in the United States with an insurance-claims data base. *Circulation* 1993;87:1489-97.
4. Lin GA, Dudley RA, Lucas FL, Malenka DJ, Vittinghoff E, Redberg RF. Frequency of stress testing to document ischemia prior to elective percutaneous coronary intervention. *JAMA* 2008;300:1765-73.
5. Wijns W, De Bruyne B, Vanhoenacker PK. What does the clinical cardiologist need from noninvasive cardiac imaging: Is it time to adjust practices to meet evolving demands? *J Nucl Cardiol* 2007;14:366-70.
6. Wijns W, Kolh P. Appropriate myocardial revascularization: a joint viewpoint from an interventional cardiologist and a cardiac surgeon. *Eur Heart J* 2009;30:2182-5.
7. De Bruyne B, Sarma J. Fractional flow reserve: a review. *Heart* 2008;94:949-59.
8. Gerber TC, Carr JJ, Arai AE, et al. Ionizing radiation in cardiac imaging: a science advisory from the American Heart Association Committee on Cardiac Imaging of the Council on Clinical Cardiology and Committee on Cardiovascular Imaging and Intervention of the Council on Cardiovascular Radiology and Intervention. *Circulation* 2009;119:1056-65.
9. Servomaa A, Tapiovaara M. Organ dose calculation in medical X ray examinations by the program PCXMC. *Rad Prot Dos* 1998;80:213-9.
10. Hart D, Jones DG, Wall BF. Estimation of effective dose in diagnostic radiology from entrance surface dose and dose-area product measurements. Report of the National Radiological Protection Board—R262. London: Her Majesty's Stationery Office, 1994.
11. Bogaert E, Bacher K, Thierens H. A large-scale multicentre study in Belgium of dose area product values and effective doses in interventional cardiology using contemporary X-ray equipment. *Rad Prot Dos* 2008;128:312-23.
12. Bogaert E, Bacher K, Thierens H. Interventional cardiovascular procedures in Belgium: effective dose and conversion factors. *Rad Prot Dos* 2008;129:77-82.
13. Fazel R, Krumholz HM, Wang Y, et al. Exposure to low-dose ionizing radiation from medical imaging procedures. *N Engl J Med* 2009;361:849-57.
14. Einstein A, Henzlova M, Rajagopalan S. Estimating risk of cancer associated with radiation exposure from 64-slice computed tomography coronary angiography. *JAMA* 2007;298:317-23.
15. Committee to Assess Health Risks From Exposure to Low Levels of Ionizing Radiation, National Research Council. Health Risks From Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2. Washington, DC: National Academies Press, 2006.
16. National Council on Radiation Protection and Measurements (NCRP). Risk Estimates for Radiation Protection. Report No. 115. Bethesda, MD: National Council on Radiation Protection and Measurements, 1993.
17. Einstein AJ, Moser KW, Thompson RC, Cerqueira MD, Henzlova MJ. Radiation dose to patients from cardiac diagnostic imaging. *Circulation* 2007;116:1290-305.
18. Hausleiter J, Meyer T, Hermann F, et al. Estimated radiation dose associated with cardiac CT angiography. *JAMA* 2009;301:500-7.
19. Mettler FA, Huda W, Yoshizumi TT, Mahesh M. Effective doses in radiology and diagnostic nuclear medicine: a catalog. *Radiology* 2008;248:254-63.
20. Legale P, Schiele F, Seronde MF, et al. One-year outcome of patients submitted to routine fractional flow reserve assessment to determine the need for angioplasty. *Eur Heart J* 2005;26:2623-9.
21. Mehran R, Aymong ED, Nikolsky E, et al. A simple risk score for prediction of contrast induced nephropathy after percutaneous coronary intervention: development and initial validation. *J Am Coll Cardiol* 2004;44:1393-9.
22. Christou MA, Siontis GC, Katritsis DG, Ioannidis JP. Meta-analysis of fractional flow reserve versus quantitative coronary angiography and noninvasive imaging for evaluation of myocardial ischemia. *Am J Cardiol* 2007;99:450-6.
23. Tonino P, De Bruyne B, Pijls NH, et al., on behalf of FAME Study Investigators. Fractional flow reserve versus angiography for guiding percutaneous coronary intervention. *N Engl J Med* 2009;360:213-24.

Key Words: contrast medium ■ coronary angiography ■ fractional flow reserve ■ radiation.